HARDWARE DESCRIPTION

Fuel Cell Powerplant
P/N MC 464-0115-3030
S/N P760119

PROBLEM DESCRIPTION

When the fuel cell startup was initiated on OV-102 during the prelaunch operations for STS-83, fuel cell 2 (P760119) Cell Performance Monitor (CPM) substack 3 voltage difference remained above the OMRSD limit of 150 millivolts for an unusually long period of time. The CPM substack 3 voltage difference continued to decrease to values less than the 150 millivolts limit and a decision was made to continue the launch count based on similar CPM response on fuel cell P760116 during the startup prior to STS-79. After launch CPM channel 3 on fuel cell P760119 degraded in orbit on a steady slope toward the CPM 150 millivolts limit and the fuel cell was shutdown and safed to preclude possible reactant crossover resulting in reactant mixing within individual cells.

ANALYSIS/INVESTIGATION RESULTS

Incident

Fuel Cell P760119 was returned to the supplier for failure analysis because of abnormal Cell Performance Monitor (CPM) readings in substack 3 during OV-102 Mission STS–83. Due to limited instrumentation (i.e., inability to monitor the 96 individual cell voltages), the abnormal readings had to be interpreted as a worst case scenario, the failure of a single cell. Since such a failure would lead to reactant crossover (H_2 and O_2 reactant mixing), a decision was made to shut down and "safe" this fuel cell approximately 48 hours into the flight. This, in turn, required declaration of a minimum duration mission, and landing took place on Tuesday, April 8, 1997.

The initial indication of an abnormal condition came just prior to fuel cell start–up when fuel cell 2 (P760119) CPM readings did not respond normally to either the flow–through purge or the subsequent three pulse purges with reactants. The three fuel cells are in an inerted condition prior to these purges, and the CPM readings are not usable, although a full–scale reading of 500 millivolts (mv) is typical. With the introduction of reactants, normal CPM readings move toward the 0 to 150 millivolts acceptable band. During the fuel cell start–up period, between the "pumps on" event and the "on bus" event, the CPM readings further converge toward the acceptable band. Over the next two hours, the individual fuel cells come to both thermal and electrolyte concentration equilibrium, and the CPM readings reach a relatively stable condition. In contrast, at the initiation of the Fuel Cell 2 start–up sequence for STS–83, all three CPM channels remained at the 500 millivolts full–scale reading through both the flow–through and pulse purges, responding only shortly before the "pumps on" signal was given. At this time channel 3 ramped up from 160 millivolts to 446 millivolts, and then decreased to about 320 millivolts by the time the

fuel cell was placed on the bus. Over the next several hours, the output from this channel continued to decrease toward its value of the previous flight. Additionally, a special 10–minute purge was conducted to ensure that the CPM imbalance was not the result of incomplete inert removal, to which the CPM did not respond, and it was noted that channel 3 was very sensitive to the high load calibration test. A "real–time" review of data from other flights found this behavior to be similar to the behavior of CPM channel 3 on P760116 during the start–up for mission STS–79, except for the magnitude of the readings. During STS–79, CPM channel 3 data stabilized at acceptable values, and the fuel cell completed a very normal mission. An additional mission was later accomplished with this fuel cell with satisfactory operation. Based on this precedent, a decision was made to clear fuel cell P760119 for launch since CPM channel 3 appeared to be stabilizing.

After launch, CPM channel 3 continued to degrade in orbit on a steady slope toward the CPM's 150 millivolts limit, having apparently passed through the "zero" point at the pre–launch load adjust. Attempts to stabilize channel 3 by reducing fuel cell load only succeeded in slightly reducing its absolute value, but the trend continued. As this value approached 150 millivolts, the fuel cell was shut down approximately 48 hours after launch (about 60 hours after fuel cell start–up). Subsequent to the shutdown, the fuel cell was safed, a procedure designed to deplete the fuel cell of reactant gases and leave it in a safe condition. This is accomplished by removing the fuel cell from the Orbiter electrical bus, closing the spacecraft reactant supply valves, and allowing the fuel cell to cool. (The hydrogen supply valve failed to close but the oxygen supply valve closed, allowing the regulator to vent down the hydrogen side). As the coolant exit temperature falls, the fuel cell sustaining heater activates. This electrical load (approximately 30 amps) results in consuming the trapped residual reactant gases stoichiometrically, as monitored by observing a decrease in the fuel cell coolant pressure to less than 15 psia (in this case, to about 8 psia).

A second observed anomaly relative to the start–up of P760119 for mission STS–83 involved open circuit voltage. During processing prior to a mission, the fuel cells are left in a "cathode–activated"/helium–inerted state, whereby the open circuit voltage is usually less than 2.0 volts. The open circuit voltage remains at this low level until the helium is purged out for fuel cell start–up, and full open circuit voltage is established when hydrogen and oxygen reactants are introduced. However, various purging/inerting operations in OV-102 resulted in leaving some mixture of helium and oxygen in the spacecraft oxygen manifold.   The hydrogen manifold, however, remained inerted with helium. This helium–oxygen mixture, aided by a delivery mechanism, i.e., diffusion and minor fuel cell regulator leakage entered the cells closest to the accessory section (substack 3, cells 96, 95, 94, etc.) which are monitored by CPM 3. As a result, the open circuit voltage of P760119 rose to greater than 18 volts weeks before the pre–start purge with reactant gases. When the pre–start purging was completed, the open circuit voltage of P760119 was 39.4 volts (near theoretical). The open circuit voltage is typically around 36.5 volts.

Near theoretical fuel cell open circuit voltages (over 39 volts) have only occurred two other times in the history of the Space Shuttle Program, and only at KSC, and only since STS–79 in September 1996. FC3 (P760116) experienced this phenomena twice. The first occurrence was on STS–79, after which P760116 had an unusual CPM 3 signature. However, since the CPM 3 data eventually stabilized, the behavior of P760116 on STS–79 formed the basis for declaring P760119 acceptable for launch on STS–83. The second occurrence was during the next flight of P760116, STS–81, in January 1997. This time, however, the unusual CPM 3 signature did not recur.

Fuel cell P760116 was returned to the supplier to support the P760119 investigation since it had experienced similar abnormal CPM 3 readings during STS–79, including the higher–than–normal open circuit voltage during pre–start reactant purging. Testing of P760116 at the supplier showed normal open circuit voltages, start–up characteristics, and operation on load. A series of special testing was conducted over several days trying to induce high open circuit voltage readings. Controlled amounts of oxygen were seeped into the oxygen supply manifold connected to P760116 in an attempt to duplicate conditions of a partially inerted oxygen manifold at KSC. Open circuit voltages in the 10 to 20 volt range were desired in an attempt to simulate the open circuit voltage observed on P760119. However, each attempt resulted in significantly overshooting this range, and testing was discontinued.

A partially inerted spacecraft oxygen manifold, combined with diffusion and minor regulator leakage, is believed responsible for creating increased open circuit voltage in inerted fuel cells. Moreover, this situation is then suspected of causing the near theoretical open circuit voltages when full reactants are introduced, which in turn, is suspected of resulting in both P760116's and P760119's abnormal CPM 3 readings. The electrochemistry for this scenario is sound, and a plausible hypothesis was developed. However, definite proof that this was the cause of the STS–83 incident could not be demonstrated. Since the abnormal CPM 3 behavior happened only once on P760116, although there were two high open circuit events involving this fuel cell, the time and degree of exposure of oxygen to an inerted fuel cell are likely a factor. A summation of this hypothesis is presented under Electrochemical Analysis, 1) High Open Circuit Voltage.

In support of this investigation, a fault tree was prepared and the subsequent testing and analysis closed out various branches of this tree.

Failure Analysis Testing

Fuel Cell P760119 was returned to the supplier on April 14, 1997, for failure analysis testing and investigation. Prior to its return, special handling procedures were used at KSC for deservicing, removal and packaging to protect/preserve as much evidence as possible. The ultimate goal was to be able to run the fuel cell as-is once it was returned to the supplier. Despite a desire to return the fuel cell in its safed state, safety/transportation concerns at KSC dictated the fuel cell be pulse purged with helium to ensure complete removal of all hydrogen and oxygen reactants.   During these pulse purges it was observed that the coolant system pressure rose to about 73 psia with each pulse which is higher than normal. Prior to removal of P760119 from the Orbiter vehicle, a visual inspection was conducted with special attention given to all fluid and electrical interface connections. No anomalies were found. During removal, special effort was made to maintain the fuel cell in a horizontal position to minimize movement of any internal fluids. Also, the normal water drain was not performed. The fuel cell was then mounted into a shipping cradle, bagged in plastic with desiccant, mounted onto a wooden skid, and boxed. Shipping was done via an air–ride truck with 24–hour service from the OPF to the supplier.

Upon arrival at the supplier on April 14, the fuel cell was uncrated, photographed and inspected. Again, there was no evidence of physical damage or external fluid leakage. Phenolphthalein checks of the reactant gas purge and supply fittings were negative, with no indication of KOH. Similarly, a halide sniff test of these same fittings was negative for the presence of FC40 coolant. The oxygen inlet and dual–feed fittings, as well as the hydrogen make–up fitting, were removed from the fuel cell. These three locations were halide sniffed and a limited–access boroscopic inspection was made of the manifolds; the halide sniff indications were negative and there were no unusual visual findings. The H_2 pump/separator drain plug was removed and approximately

45 cubic centimeters of residual product water was captured. Both the drain port and the removed water were halide sniffed with no indications of the presence of FC40 coolant. Subsequent laboratory analysis of the product water found nothing unusual.

Fuel cell P760119 was then mounted in test stand X–578 in the landing orientation for failure analysis testing, and a coolant ullage check was done to verify the proper 27 cubic inches of FC40 coolant in the accumulator. This check determined the volume to be approximately 35 cubic inches, indicating the presence of gas in the coolant. The presence of gas bubble(s) is expected, but the volume of the bubble(s) was likely larger than normal because of the low pressure resulting from the safing procedure. A coolant–to–reactant crossover test was conducted to verify coolant system integrity. This was achieved by disconnecting the oxygen supply fitting to the accumulator, and pressurizing the accumulator using an external nitrogen source. A nitrogen pressure of 15 psig was set on the accumulator and the decay was monitored overnight. A 1 psig decay was recorded in 13 hours, equivalent to a volume of about 3 cubic inches. Due to an 8°F overnight drop in ambient temperature, however, this decay test was inconclusive. In preparation for the reactant–to–reactant crossover test, the accumulator oxygen fitting was then reconnected and a pressure gage was installed at the unused port of the hydrogen system at the accessory pressure plate. The initial step was pressurization of the regulator which resulted in O_2 side venting at about 71 psia. This high O_2 venting pressure, which also had been observed at KSC during the post–flight pulse purging, results from O_2 supply valve leakage in the regulator. This is a known phenomena associated with aging of the regulator elastomers.

To conduct the reactant–to–reactant crossover test, the O_2 system was pressurized with helium to 15 psig, while leaving the H_2 system at ambient pressure. Over the next 9.5 hours, there was no change in H_2 system pressure, signifying no crossover. The standard nitrogen diagnostic test was then successfully conducted, with the average decay being 32 millivolts indicating no crossover and no port plugging.

The fuel cell then underwent four start/stop cycles, each with a nitrogen diagnostic test, cathode activation and an overnight cooldown between runs. The first start was made from the landing orientation. The second, third, and fourth starts were in the right–hand launch orientation simulating fuel cell orientation on the launch pad. CPM channel 3 was in the same general region as it was in Mission STS–83, just prior to fuel cell shutdown. This indicates that (1) the main goal of the test plan, i.e., to be able to run the fuel cell as is, had been accomplished, (2) that the fuel cell condition at the time of shutdown had been captured, and (3) that the safing procedure and pulse purging had not adversely affected the fuel cell. The high open circuit voltage that had occurred on P760119 prior to start–up in OV102 did not appear during the testing at the supplier. Also the wide CPM 3 shifting experienced in the field did not repeat. All three CPM channels were very stable during each run, with CPM channel 3 coming down about 10 millivolts each run. This supports the hypothesis that the fuel cell experienced some form of externally induced upset. Toward the end of the third run, gas samples were taken from both the H_2 and O_2 purge ports for laboratory analysis. No contaminants were found. CPM readings from all four runs were compared to cell voltages being measured during the tests. The CPM readings were consistently accurate, and in agreement with the individual cell voltages. The individual cell data compared to the initial acceptance test at the supplier indicate that the CPM channel 3 imbalance is due primarily to higher performance decay in cells 65 through 80 than that seen in cells 81 through 96. To determine whether this situation was unique or common, a comparison of the initial acceptance test performance with the last acceptance test performance was made for each of the

21 fuel cells. The performance decay of each 16–cell group was compared to its substack partner and the difference in decay (equivalent CPM reading) was evaluated statistically. This demonstrated that for the 63 data points, some with much longer operating times, P760119 CPM channel 3 was clearly an outlier at about 4 sigma.

After completion of the fuel cell testing, the accessory section from P760119 was demated and the power section was run as a separate unit. This run consisted of a repeat of its original acceptance test. There were no unusual performance observations. The cells in the lower half of substack 3 (65 through 80) again demonstrated slightly more decay since new, and more decay than cells 81 through 96. However, the min–to–max spread over all 96 cells was sufficiently close that no cell was a statistical outlier. Manufacturing dates and initial performance did not show any correlation. The power section met all acceptance criteria.

Parallel to the fuel cell testing, an electrical system analysis via computer simulation was performed to determine whether the observed CPM output of substack 3 was fuel cell related or instrumentation related (i.e., CPM circuitry, wiring harness, cell voltage pin crimp assembly). An additional objective was to identify a failure scenario that was consistent with the observed in–flight CPM output data for substack 3. The analysis was conducted under the assumptions that failures associated with the CPM circuitry *common* to both substack voltage and self-test monitoring are discounted due to observed proper operation during fuel cell testing, and that the self-test circuit operated correctly throughout the observed substack voltage anomaly (i.e., the 50 millivolts signal was detected every 7 minutes).

Potential failures considered external to the CPM included increased series resistance in pin or wire connections from poor solder joints, bad crimp connections, damaged wire or contact contamination, and shorts (or low resistance) paths from harness wire insulation breakdown, wire bundle contamination or a CPM connector failure (isolation or in–line filter). Potential failures internal to the CPM that were considered include a partial malfunction of the analog switch, or a failure in the negative side of the absolute magnitude amplifier circuitry where 6 percent of the CPM components are not tested during the self-test mode. Also, simulations were run of several shunt–resistance paths across the exterior of the substack.

The result of the electrical system analysis was that although the observed anomaly could have been electrical in nature, it was unlikely to be CPM related. Simulations of increased or decreased connection resistance, stack exterior shunt currents, or CPM internal device failures could not duplicate the anomaly in magnitude and variation. Additionally, the documented component failure history did not match the observed data. A review of test data from both the fuel cell testing and electrical system simulation leads to the conclusion that the fuel cell, its CPM, and the electrical communication between the two are (and has been) functioning properly.

In summary, the initial inspections and testing conducted on P760119 upon return to the supplier showed no loss of integrity related to the events which occurred during STS–83. There were no visual nonconformances, and safing of the fuel cell in orbit produced no adverse effects. P760119 was able to run as-is several times with all parameters normal. There were no coolant leaks, crossover, or electrolyte flooding conditions; there were no electrical or instrumentation problems that could be related. All performance criteria established for acceptance testing power sections were met. It was the minor (millivolt) differences in performances of an unusual grouping of approximately 24 cells, which resulted in the abnormal CPM 3 indications which had to be interpreted as the loss of a single cell. The performance variations in this unusual grouping lend credence to the hypothesis of an external event affecting the performance of these cells.

Fuel Cell Teardown Investigation

Having demonstrated proper operation of the fuel cell, it was subsequently disassembled for investigation of the individual components. The power section was demated from the accessory section, and both sections (after testing) were completely torn down. The key components were subjected to varying levels of analysis depending on their possible contribution to the incident. These analyses could consist of any combination of a visual inspection, functional check or total teardown and analysis. The following is a summation of the results:

- Cell voltage harness PN 800673, SN F320 - The cell voltage harness was returned to its supplier for a repeat of its original acceptance test. The harness successfully passed all requirements for high potential and insulation resistance tests. All parts of the continuity test also passed with the exception of the wire from connector J6 to contact pin 38 at the power section end. This wire was found to have a resistance of 0.106 ohms, exceeding its allowable limit of 0.070 ohms. The wire was judged not to have any significance relating to the STS–83 incident since it does not go to the CPM, plus it exceeded its limit by an insignificant amount. Its function was to provide the voltage potential to ground instrumentation for computing the voltages of cells numbers 37 and 38. It is not connected during flight.

- Cell Performance Monitor (CPM) PN 811046–01, SN HH649 - The CPM was removed from the fuel cell and returned to the supplier, Aerospace Avionics, for an external physical examination and an abbreviated acceptance test FCTS 4148. The inspection of the CPM case and connectors J36 and J37 showed no indication of any contamination or mechanical damage. The abbreviated acceptance test (input, isolation and operational) results were all within specification limits, and the test data recorded were in agreement with previous acceptance test data obtained at the time of manufacture of this CPM. There was no evidence to indicate that the CPM operated abnormally at any time.

- Reactant regulator PN 811924–01, SN JO64 - Regulator SN JO64 was hand carried to the supplier for TT&E after the six filter fittings and two check valves had been removed at United Technologies Research Center (UTRC) to be checked for possible contaminants. It should be noted that this regulator's O_2 inlet fitting O–ring did leak prior to Mission STS–83 and was replaced by KSC. The regulator had a normal external appearance, although the H_2 purge return port was slightly darkened. New filter fittings and check valves were installed prior to testing.

  Testing showed the pressure output vs. flow to be close to, but slightly below, the original as–built results. At setpoint, the O_2 pressure was 47.6 psig vs. 49.0 psig as–built; the H_2 pressure was 42.5 psig vs. 43.6 psig; and an O_2 supply leak was evident. The leak rate was sufficient, when left at zero flow, to build up pressure from 54.5 psig to 57.0 psig in five minutes, at which point the O_2 vent valve operated to relieve the excess pressure. There was no other valve leakage or leakage to environment at this time. The H_2 and O_2 diaphragms met the leakage specification of zero bubbles in 30 minutes. Purge valve flows were within specification limits.

Disassembly showed the interior of the H_2 and O_2 bodies to be free of corrosion and contaminants. The O_2 diaphragm ruptured during the environmental leak test because the O_2 supply leak had caused excessive pressure buildup which could not be relieved by the vent valve since the vent port is capped for this test.

Elastomers, especially on the O_2 side, showed some deterioration. The O_2 high pressure first stage O–ring had a visible crack which is the likely source of the O_2 supply leakage. The O_2 diaphragm had stiffened and hardened from an original 75 durometer to 85 durometer now. The sealing rim of both diaphragms had taken a set, resulting in only approximately 0.001 inch available pinch on the O_2 diaphragm and 0.003 on the H_2 diaphragm, as compared to the nominal 0.021 pinch when originally built.

The O_2 and H_2 bodies were flushed with distilled water and again with Genesolv solvent. The flush effluents were preserved for later analysis at UTRC to identify possible contaminants. All elastomers were removed from the bodies for possible further analysis. The remaining regulator parts were stored. In general, the condition of the regulator was considered normal for its age and operating time.

- Power section PN 811499, SN RR494 - Prior to demating the power section from the accessory section, the main insulation blanket was removed from the power section and a visual examination was performed on its exterior. No abnormalities were noted. A slight buildup of carbonates was present, but the amount was toward the low side of what would typically be expected for a power section of this age. After demating, a boroscopic examination was made of the manifolds with nothing unusual found. The only observation made was that it appeared cleaner than expected. Tie–rod stretch was measured, and the results were compared to the recorded numbers of the original build. These numbers were reviewed and the amount of creep calculated was consistent with that of a mid–life fuel cell.

  All Unitized Electrode Assemblies (UEAs) were found to have a slight amount of frame swelling at the ports, oxidation at the tips of the cathode shields, and corrosion at the UEA edges. All of this is normally expected. Additionally, several UEAs (but not all) exhibited other conditions which included slight carbonate deposits around the inside edge of the oxygen manifold, carbonate deposits over the cathode foils at the edge of the frame, and several UEAs with black areas at the edges of the active areas of the cathode, and some with gold–tinged areas adjacent to the peripheral black areas. Several of these cells from all three substacks were sent to the laboratory for further performance and chemical analysis.

  The visual examination of the magnesium separator plates found them to be in good condition. The oxygen ports and manifolds were unusually clean. There were very few plating discontinuities, and no evidence of flattened seals. Liquid and/or liquid stains were observed in 33 oxygen fields typically ranging in area from 1 to 3 square inches, although a few were larger. Two of the wetted plates were sent to the lab for analysis, the liquid being identified as KOH electrolyte. The positions of these plates did not correlate with the locations of cells with the observed minor performance loss.

Electrochemical Analysis

Electro–chemical analysis focused on two areas: (1) the identification of the cause of high open circuit voltage, and (2) post–test analysis of cell electrodes.

1) <u>High Open Circuit Voltage</u>:

The very high open–circuit voltages observed on fuel cell P760116 and fuel cell P760119 in the field are not above the theoretical value of 40.32 volts possible for the operating conditions of the fuel cell. Experiments performed to induce these high open circuits included storing electrodes in 100% oxygen for several days, changing the electrolyte concentrations, freezing electrodes/electrolyte, and running activation cycles on new and used cathodes. Oxygen was used in these tests in an attempt to show that oxygen reintroduced into an inerted fuel cell can lead to high open circuit voltage and subsequent performance shifting. However, these tests were unsuccessful in producing these effects.

The electrochemistry of nickel was also investigated to determine if the anode potential was affected by nickel oxidation. The open circuit voltages of platinum–palladium, with and without the nickel ERP, were studied as a function of oxygen partial pressure. These tests were also inconclusive.

However, a hypothesis was later developed for P760119 which electrochemically related the two anomalies, high open circuit voltage and subsequent abnormal CPM 3 behavior. As a starting point, this hypothesis required oxygen to have entered the cathodes of some cells in substack 3 after the fuel cell had been inerted with helium for approximately 3 months before the launch. The source of oxygen is believed to be from an incomplete inerting of the spacecraft oxygen manifold and a leaking reactant regulator, as previously discussed.

With oxygen available to the cathodes of some cells in substack 3, and helium on all the anodes, a voltage is developed which causes current to flow in any electrically connected circuit. This includes the remaining cells in substack 3 which were not exposed to oxygen, but which are electrically connected in series, and substack 2 and substack 1 cells, which are inerted, but electrically connected in parallel, as well as any shunt current paths.

In substack 3, the cathodes exposed to oxygen respond with the normal cathode reduction reaction, while the anodes (since there is no available hydrogen) respond by first oxidizing the nickel ERP, and then start dissolving the palladium and platinum catalyst into the electrolyte. The rest of the cells in substack 3, which have not been exposed to oxygen, will also oxidize the nickel ERP and start dissolving the palladium and platinum in their anodes. However, the cathodes of these cells (without oxygen) will reduce water in the electrolyte causing hydrogen to evolve. In the case of these cells, the palladium and platinum will not remain dissolved in the electrolyte, but will migrate and plate out onto the gold–platinum cathode catalyst layer.

In substacks 1 and 2 (because the current is electrically reversed by the nature of the stack connections), the anodes act as cathodes and vice versa. On the anodes, a water reduction reaction produces hydrogen evolution and on the cathodes there is some platinum dissolution.

This scenario creates the near theoretical open circuit voltage once full reactants are applied to the fuel cell. The gold–palladium catalyst formed in many of the substack 3 cells is a better oxygen reduction catalyst than gold–platinum and results in the higher open circuit voltage level.

During subsequent operation of the fuel cell, the nickel ERP oxidation and palladium deposition on the cathodes change cell performance levels in the substack 3 cell groupings. The CPM 3 readings respond accordingly, first showing an increase and then a decrease in performance levels. Most likely the difference are caused by electronic resistance changes through the ERP nickel oxide films as the nickel oxide is reduced. Decay differences between cells exposed to oxygen and those not exposed in substack 3 may be the result of palladium and platinum plating from the anode to the cathode affecting the catalyst surface/structure, thereby resulting in performance loss.

Although this hypothesis is plausible, it has not been proven to be correct. Furthermore, proof is difficult because the subsequent operation of the fuel cell after these events reverses the reactions and removes the necessary evidence to support it.

2) Post–test Analyses:

Used electrodes from P760119, both anodes and cathodes, were taken from cells with varying decay characteristics. Cathode and anode samples were cut from the oxygen inlet, the center of the cell and along the edge(s). Selected cathode samples were evaluated for oxygen reduction performance with 100% oxygen and 20% oxygen (balance nitrogen); selected anode samples were evaluated for hydrogen oxidation performance. Some electrodes were also evaluated electrochemically for surface area, and a group of samples was chemically analyzed to determine noble metal loading. Other samples were submitted for x–ray diffraction to determine the crystallite structure of the catalysts.

The above analyses did not result in showing significant differences between samples from cells classified as good or bad, based on decay characteristics. None of the data strongly suggested anything beyond normal aging characteristics, although localized areas did show some unusual changes in diffusion losses and activation levels. However, in support of the electrochemical hypothesis proposed, analysis of the palladium (and platinum) content of the anodes as a function of cell position tended to show more loss in substack 3 than in substacks 1 and 2, although this analysis was not conclusive and normal operation would reverse the process which caused the original high open circuit voltage and performance shift.

This investigation also focused on finding evidence of contaminant ingestion in the fuel cell fluids and components. Sampling was based on a systematic evaluation of the fuel cell as received from NASA/KSC, during the supplier testing, and after disassembly.

- A small quantity of water taken from the hydrogen pump/separator drain (as received) was subjected to a battery of tests to identify contaminants not ordinarily found in the water. Additional tests were also performed to specifically identify the presence of FC40 fluorocarbon coolant or other organic carbon species. A similar quantity of water from fuel cell P760116, a fuel cell which had experienced a similar performance anomaly, was also tested for comparative purposes. All tests were negative. Product water taken from P760119 during performance testing at the supplier was also analyzed using the criteria for normal acceptance tests with the addition of analysis for organic compounds and other metallics. These results were also negative.

- FC40 coolant from the fuel cell was analyzed for the presence of KOH. None was found.

- Reactant gases purged through the fuel cell were collected and analyzed for evidence of organic compounds. No contaminants were found.

- Eight fittings removed from the reactant regulator were subjected to a solvent flush (50:50 hexane:methylene chloride) for analysis of organic contamination followed by a water flush for analysis of anionic species. Results were negative. During disassembly a substance found at the oxygen inlet fitting was analyzed and confirmed to be Krytox, a fluorocarbon grease used in the regulator.

- After disassembly of the regulator at the supplier, O–rings, diaphragms, and flushing fluids were returned to the supplier for further analyses. Genesolv and water, used on both the H_2 and O_2 bodies of the regulator, were analyzed for contaminants. Evidence of Viscosil, the GE silicone damping fluid from the centerbody, was found in the O_2 body but was determined to have occurred during the testing at regulator supplier when the O_2 diaphragm burst and leaked Viscosil. Minor traces of Krytox, commonly used in the regulator seals, were also detected, but no other organic contamination was noted. Tests on water flush samples for anionic species were also negative.

- Tubing and fittings from the accessory section were all solvent and water flushed, and then analyzed for contaminants. Results were negative.

- Several UEAs were selected based on substack performance and cell decay, and subjected to various spectroscopic and x–ray investigations to identify abnormalities or contaminants. Cell components, matrix and catalyst layers were subjected to wet chemical techniques for detection of trace contamination and/or unusual component degradation. Nothing unusual was found beyond what is perceived as normal aging. There was no significant difference between any of the cells analyzed, although substack 3 cells tended to show more palladium and platinum loss than substacks 1 and 2 cells.

- Three UEAs were analyzed for total electrolyte and carbonate content. All were normal.

- There was no evidence of any chlorofluorocarbon (CFC) in any of the catalyst layers, matrices or ERPs that were analyzed.

- Two separator plates with minor liquid and solid contamination in the field area were analyzed for identification of the material.   The material was confirmed to be KOH with no other contaminant species. The presence of KOH deposits is not considered abnormal.

In summary, the post–test teardown investigation and analysis of P760119 found no conclusive abnormalities of any significance relative to the STS–83 incident. All significant major components, power section, cell performance monitor, cell voltage harness and reactant gas regulator were tested by their suppliers and found to meet original specifications with only minor exceptions. Both the power section and the regulator were completely disassembled, again with only minor anomalies observed. Several removed components, as well as samples of fuel cell coolant, product water and purged reactant gases were sent to laboratories for chemical and/or electrochemical analysis. The loss of palladium and platinum tends to support the hypothesis that traces of oxygen in the inerted fuel cell led to an elevated open circuit voltage, oxidation of the ERP, and transfer of palladium and platinum.

Conclusion

The failure analysis of P760119 has been completed. No hard physical evidence was found that could explain the performance changes occurring in a group of approximately 24 cells (and the resulting CPM channel 3 shifts) experienced during Mission STS–83. Since no foreign material/contaminant was found, the most credible scenario implies an abnormal external event affected a group of cells prior to start–up.

It has been hypothesized that this external event was the presence of oxygen in the oxygen side of substack 3 of fuel cell P760119 at a time when the fuel cell was supposed to be inerted with helium. This event, with time, causes oxidation of the nickel ERP and dissolution of palladium and platinum in the anodes. Migration and plating of the palladium onto the cathode catalyst causes high open circuit voltage once full reactants are applied to the fuel cell. During subsequent operation of the fuel cell, the nickel ERP oxidation and palladium deposition on the cathodes change cell performance levels in the substack 3 cell groupings, and the CPM 3 readings respond accordingly.

Since subsequent operation of the fuel cell removes the evidence, the only indication found during post–test analysis was a "tendency" toward more loss of palladium (and platinum) in the anodes of substack 3 cells than in substack 1 and 2 cells, although this was not conclusive. Post–event fuel cell testing at the supplier verified the CPM channel 3 signature observed in orbit just before fuel cell shutdown and safing, and confirmed that the fuel cell did not fail, and in fact, met all performance acceptance criteria. During STS–83, the CPM instrumentation could not be used to determine what was happening, and the worst case (single cell failure) had to be assumed. Comparison of CPM readings with readings of the single cell instrumentation at the supplier during these tests, plus the results of the CPM analysis at the supplier's facility, showed the CPM was functioning properly, and its output was real.

Because the presence of oxygen in an inerted fuel cell is the potential external event that causes the hypothesized sequence to begin, KSC personnel have taken steps to reduce oxygen by conducting additional pulse purges of the vehicle storage tanks and plumbing. Reactant regulator redesign is being tested to improve the regulator elastomers and reduce the occurrence of regulator leakage.

FAILURE HISTORY

This failure (CAR 83RF01) is the first occurrence of a fuel cell exhibiting high open circuit voltage prior to a flight and then having an anomaly diagnosed as a potential reactant crossover failure mode. Fuel cell P760116 is the only other fuel cell that exhibited high open circuit operation during fuel cell startup for prior to STS-79 and STS-81 (CAR KB3771). The P760116 CPM signature trace during startup for STS-79, although unusual, has been determined to be in-family. Also fuel cell P760116 CPM values returned to normal values prior to launch and remained normal throughout the STS-79 mission and did not result in a diagnosis of a potential reactant crossover failure mode. The three incidents of crossover leakage detected at the supplier are documented in CAR AC9841 where a cell leak was detected during a power section pressure check; CAR KB1858 where two cell leaks were detected during diagnostic testing; and CAR AE1104 where three cell leaks were detected during diagnostic testing. The failure analysis supporting CAR AE1104 is ongoing.

CORRECTIVE ACTION

KSC procedure changes have been made since STS-83 to reduce residual oxygen concentration in the orbiter oxygen supply system interfacing with the fuel cell oxygen supply port. The procedures V1067 and V1091 for the post drain oxygen inert pulse purge have been changed to add one additional helium pulse purge. The procedure V1093 for the pre-Cathode Activation oxygen manifold inert pulse purge has been changed to add seven additional nitrogen pulse purges. The procedure V1103 for the EMU Functional for the post test oxygen manifold inert pulse purge has been changed to add seven additional helium pulse purges. The mechanism that allows ingestion of orbiter oxygen system inerted gas into the fuel cell is being improved. The fuel cell oxygen system reactant regulator leakage frequency should be reduced by the alternate regulator elastomer improvements. The current regulator neoprene elastomers deteriorate in a high pressure, high temperature oxygen environment and replacement AFLAS and EPDM elastomers will be tested in a regulator under simulated operations for 3000 hours. Based on successful test results it is estimated that reactant regulators containing these improved elastomers will start becoming available in approximately one year.

Launch Commit Criteria changes have been made to identify out-of-family CPM conditions that could indicate a problem in a cell or group of cells in a fuel cell prior to launch. This new set of criteria was determined by reviewing the data from STS-26R to STS-83 to determine the maximum observed changes. The stabilization limit of 18 millivolts from the time period of fuel cell performance calibration completion plus one hour to start of prelaunch conditioning accepts all data points considered in-family while rejecting the STS-83 data point of 88 millivolts. The sensitivity limit of 28 millivolts, from the prelaunch conditioning data, accepts all data points during a load change considered in-family while rejecting the STS-83 data point of 46 millivolts. The OMRSD has been changed in a similar fashion to the LCC to identify out-of-family CPM conditions.

The fuel cell monitoring system (FCMS) has been designed and tested for first use on STS-87. The FCMS is used as a backup to the current CPM to provide additional individual cell health monitoring in the event that the CPM data indicates an abnormal condition inflight. The FCMS, if available at the time of STS-83, may have precluded shutdown of fuel cell P760119 inflight.

APPROVALS:

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